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Carderock Division
Naval Surface Warfare Center

Bethesda, Maryland 20084-5000

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July 1992

Propulsion and Auxiliary Systems Department
Research and Development Report

Investigation of Power Losses in the 300 kW Superconductive Generator

by
David W. Maribo
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ABSTRACT

Previous measurements of the current collector power losses in the 300 kW superconductive generator have shown the losses to be much higher than predicted by theory. The purpose of these experiments was to isolate the source and magnitude of the power losses with more accurate experimental methods and data collection techniques. The losses could then be theoretically extrapolated to predict losses in a full scale machine for ship propulsion. The results showed that the excessive losses were fluid losses due to overfilling of the current collectors with liquid metal, and eddy current losses in the rotor bearings due to the rotation of the electrically conducting balls in the magnetic field.

ADMINISTRATIVE INFORMATION

This work was performed at Carderock Division, Naval Surface Warfare Center, formerly David Taylor Research Center, in Annapolis, Maryland under the Advanced Current Collector Technology Program, sponsored by NAVSEA 92RP3 under funding document number N0002490WX70069, program element number 63569E, work unit number 1-2712-601-57.

INTRODUCTION

The DTRC 300 kW superconductive homopolar motor and generator were built and initially tested in the mid to late 1970's (Refs 1 and 2) and were eventually used to power the Jupiter II test craft in 1980. At that time the primary goal of the project was a demonstration of superconductive electrical machinery and component technology in laboratory scale devices. These technologies include superconductive magnets, cryogenic refrigeration, and liquid metal current collectors.

The main features of the 300 kW generator are shown in Fig. 1. Electromagnetically, the generator is a one turn machine consisting of an inner stator and an outer stator connected in series with the rotor by two liquid metal current collectors as shown in Fig. 2. Excitation flux is provided by two superconductive magnets located outside of the rotor - stator assembly and contained within an iron flux shield.

To improve stability in the two liquid metal current collectors, the narrow gap braid collector was developed, and successfully tested in the late 70's and 80's. Fig. 2 shows the location and geometry of the braid collectors as well as the dimensions for the two different collectors. The rotor tip widths are sized to give approximately equal areas for the two different diameter collectors. Table 1 lists the current collector dimensions.

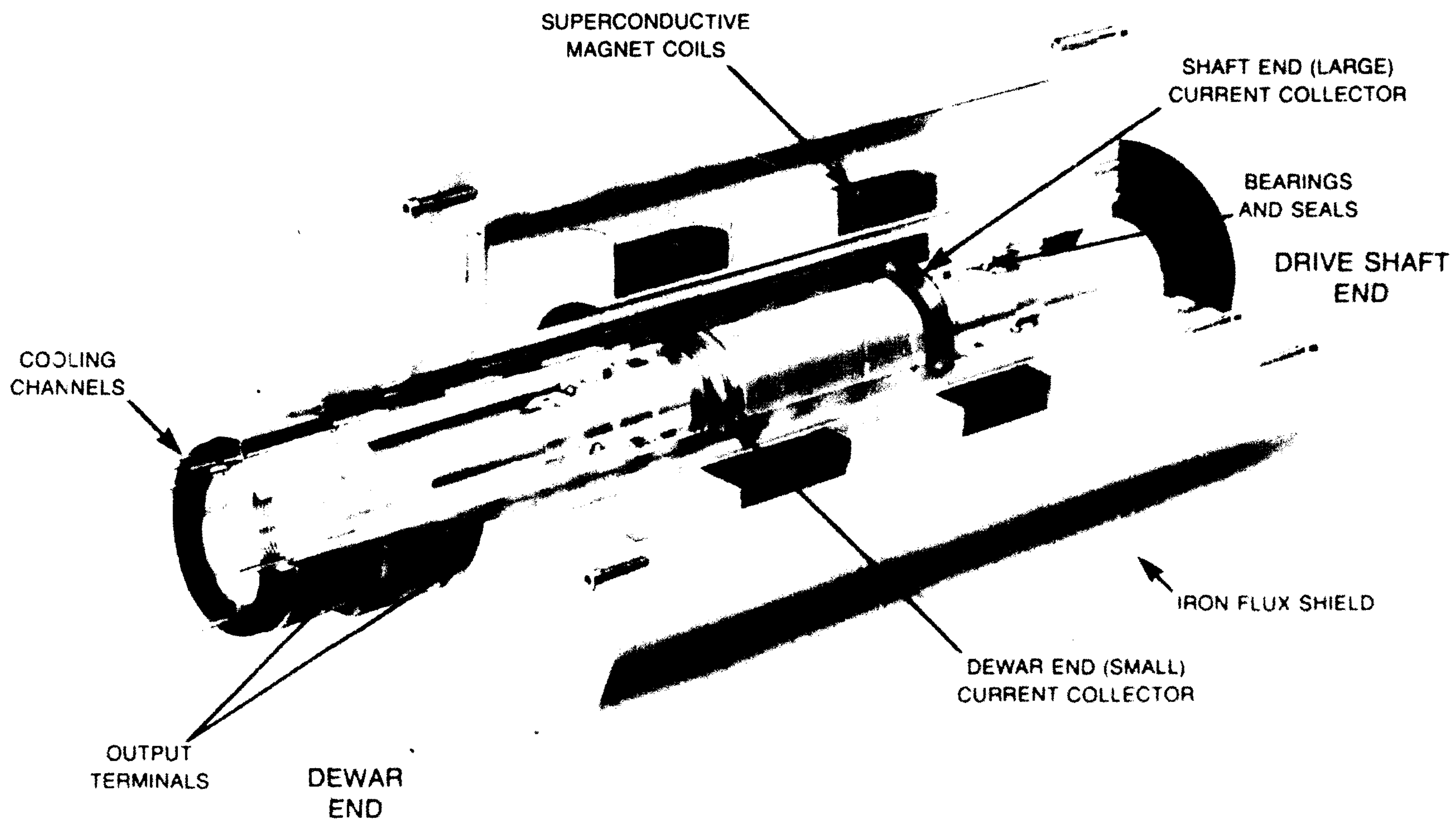

Fig. 1 300 kW superconductive generator with principle components

Current collector dimensions.

	Diameter	Width	Surface area	Tip speed (@11,000 RPM)
Dewar end collector	12.360 cm (4.866 in)	0.465 cm (0.183 in)	18.05 cm^2 (2.80 in^2)	71 m/s 233 ft/sec
Shaft end collector	14.046 cm (5.530 in)	0.414 cm (0.163 in)	18.27 cm^2 (2.83 in^2)	81 m/s (265 ft/sec)

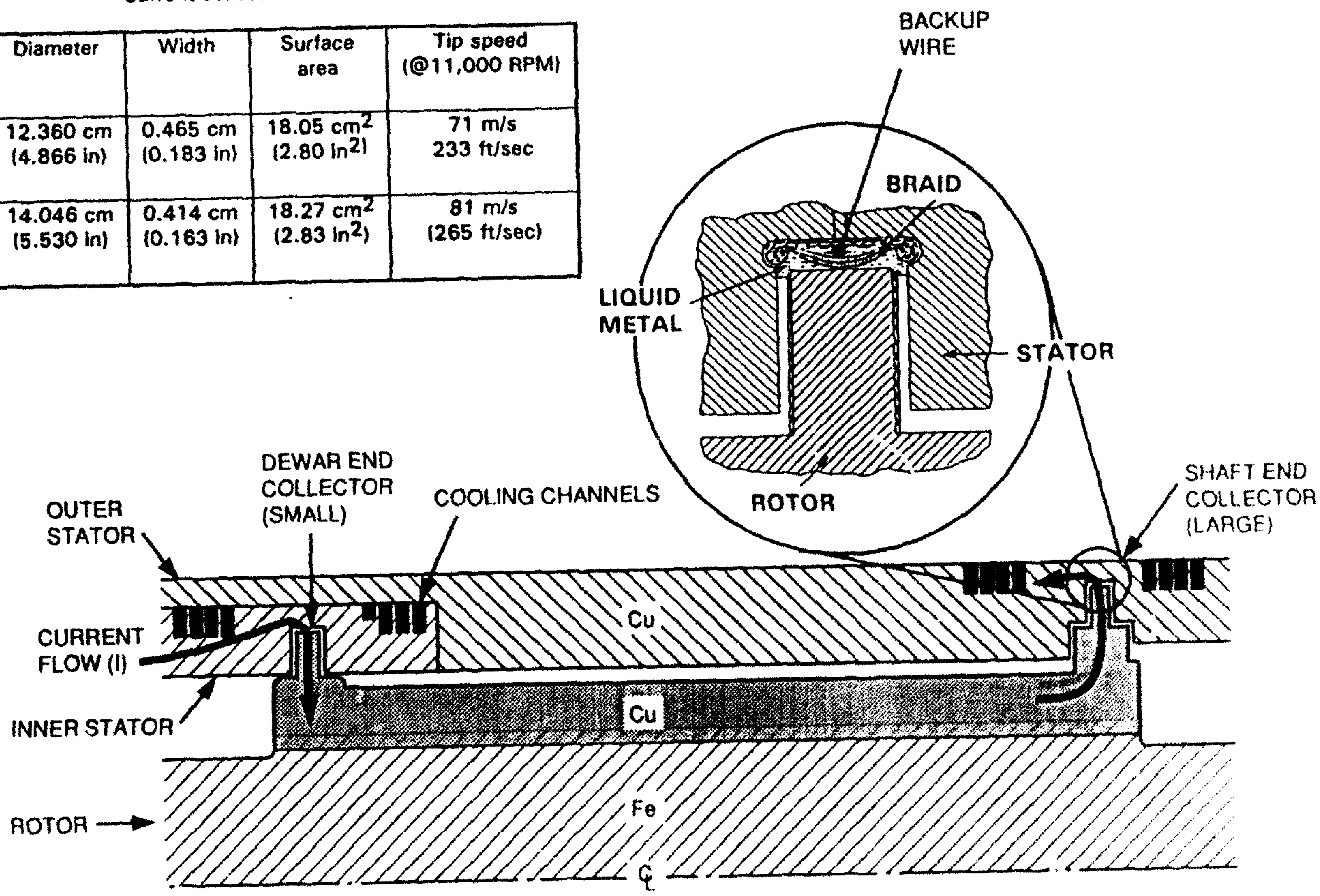

Fig. 2. Electrical arrangement of 300 kW generator.

Table 1. Current collector dimensions.

	Diameter	Rotor Width	Surface area	Tip speed (@11,000 RPM)
Dewar end collector	12.360 cm (4.866 in)	0.465 cm (0.183 in)	18.05 cm^2 (2.80 in^2)	71 m/s 233 ft/sec
Shaft end collector	14.046 cm (5.530 in)	0.414 cm (0.163 in)	18.27 cm^2 (2.83 in^2)	81 m/s (265 ft/sec)

In order to measure power losses in the narrow gap collector, several sets of data were taken in 1978 and 1979 and are described in ref. 3. These data suggested that the losses in the generator are (1) purely viscous and (2) are an order of magnitude higher than losses predicted by analytical models. The data is displayed in Fig. 3.

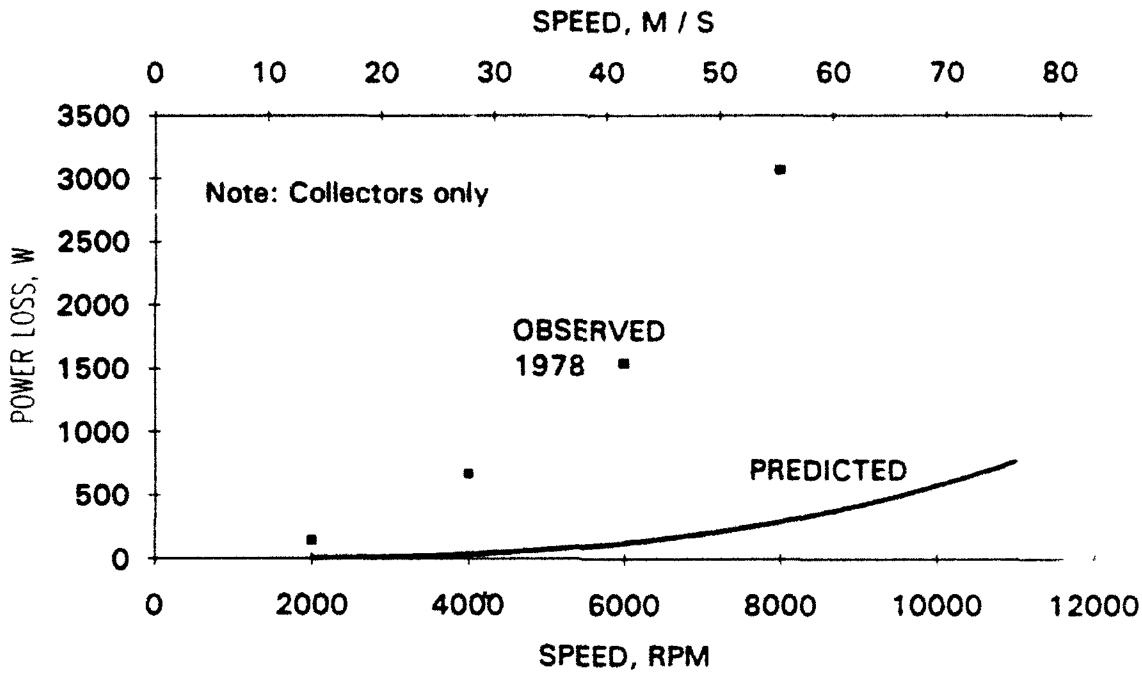

Fig. 3. Original current collector loss measurements.

The losses were much higher than predicted by the simple fluid loss model given in ref. 4, but still within reason for this machine. For example, the 3 kW measured loss shown for 8000 RPM (55 m/s average collector tip velocity) in Fig. 3, although ten times the prediction, is still only 1 percent of the 300 kW rating of the generator. However, attractive full scale machinery, in contrast, requires that the losses be the same as predicted by these models. If the losses were multiplied by the larger diameter of a full scale collector - 1.32 m (52 in.), and the resulting losses per collector were multiplied by by the number of collectors in a full scale motor, which is 40, then the collector losses would be much greater than the optimum 1 percent.

Since power testing was being done at the time, the torque transducer used was of the

339 N*m (3000 in - lb) range. The current collector losses were measured under no load conditions, which are typically less than 2.26 N*m (20 in - lbs), so the resolution of the torque transducer was insufficient for current collector loss measurements, and the accuracy of the measurements was questionable.

It was decided to reexamine these power loss measurements with a 5.7 N*m (50 in - lb) torque transducer and a much more refined data acquisition and reduction system. The many channels of data can be recorded at a much greater sampling rate - several times per second - and immediately graphed, allowing fluctuations in the data to be analyzed to a much greater degree than before. This new data will be used to refine theoretical current collector models presently under development.

DESCRIPTION OF EXPERIMENTS

The 300 kW generator was set up in the current collector test facility at DTRC. It was mechanically driven by a variable speed AC induction motor through a 3.25:1 transmission giving it a top speed of approximately 11,000 RPM. The setup is shown in Fig. 4. The close clearance braid current collectors with NaK liquid metal were the same as used in all experiments with the generator since the 1978 experiments mentioned above. The radial clearance between the braids and rotor is .025 to .050 mm (.001 to .002 inches).

The generator was tested this time in three different modes: (1) Open circuit with collectors- the generator is driven with the drive motor and the total losses are measured. (2) Open circuit without collectors; i.e. without braid or liquid metal - when subtracted from (1) bearing, windage, and seal losses are definitively measured. (3) Unloaded motoring - The generator is run as a motor by driving current through it from a power supply. The power necessary to drive it in either case is only that which is necessary to overcome the internal losses. Since transport current, and the losses associated with it, is at a minimum in the motoring case, and is absent in the open circuit case, the results are very close.

The table below summarizes the test conditions.

Table 2. Test conditions.

* Note: "collectors" refers to braid and liquid metal	SPEED	MAGNETIC FIELD CURRENT
open circuit, *with collectors	2000 - 11,000 RPM (14 - 76 m/s)	0, 30, 60, 90 amps
open circuit, *with collectors	8000 RPM (55 m/s)	0 - 30 amps
open circuit, *without collectors	2000 - 11,000 RPM (14 - 76 m/s)	0, 30, 60, 90 amps
motoring	2000 - 11,000 RPM	30, 90 amps

For magnetic field induced current collector loss calculations, accurate values of the radial and axial magnetic field components in the current collector areas are required. These fields

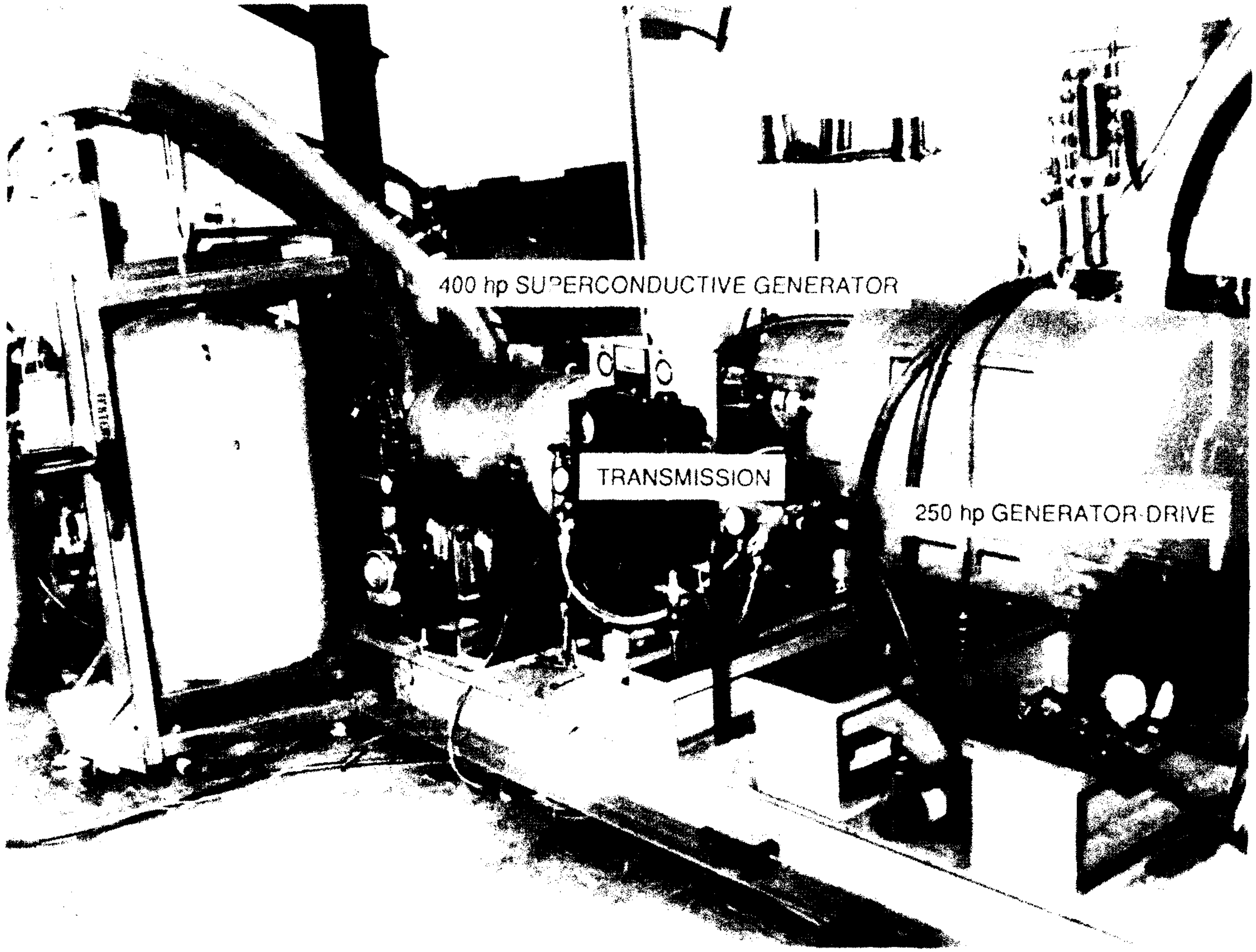

Figure 4. 300 kW generator and drive train components

have been determined using the finite element program PE2D, and are shown in table 3. The two collectors are differentiated by the names dewar end; small diameter collector nearest the output terminals, and shaft end; the larger diameter collector nearest the input drive shaft.

Table 3. Magnetic field in collector area.

	Dewar End Collector		Shaft End Collector	
Magnet Current (amps)	Radial Field (Tesla)	Axial Field (Tesla)	Radial Field (Tesla)	Axial Field (Tesla)
30 A	0.0303	0.936	0.0161	1.02
60 A	0.0567	1.96	0.0254	2.11
90 A	0.0849	2.99	0.0358	3.19

The parameters measured while varying the speed and magnetic field, were generator terminal voltage, current, torque, bearing temperature, and cover gas flow.

The ohmic losses of the collectors were obtained by running 200 amps through the generator with an external power supply while driving it at 2000 RPM and no field and subtracting the copper resistance of the machine. The resistances of the rotor and stators were measured separately by running 500 amps through them when the generator was apart.

After dryout of the generator to less than 10 PPM O_2 and H_2O to prevent NaK oxidation, the collectors were filled with 8 cc of NaK in the small diameter (dewar end) collector and 11.5 cc in the large diameter (shaft end) collector.

RESULTS

BEARING LOSSES

One of the most important accomplishments of this set of tests is the measurement of significant eddy current losses in the main rotor bearings when the magnetic field is applied. These losses account for a portion of the difference between the experimental data of 1978 and the analytical current collector model. To determine the effect of field on the generator losses, the generator was driven, open circuit, to 8000 RPM. The field current was initially 30 amps. It was decreased to 0 amps, then increased to 30 amps again. The results are shown in Figs 5 and 6.

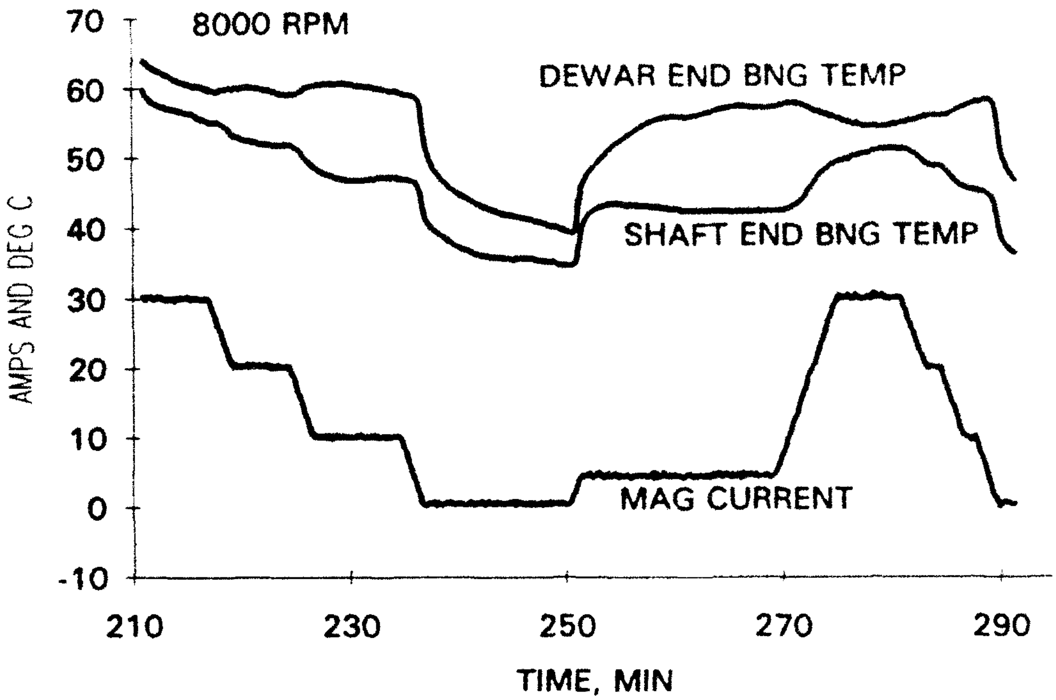

Fig. 5. Effect of magnetic field on bearing temperature.

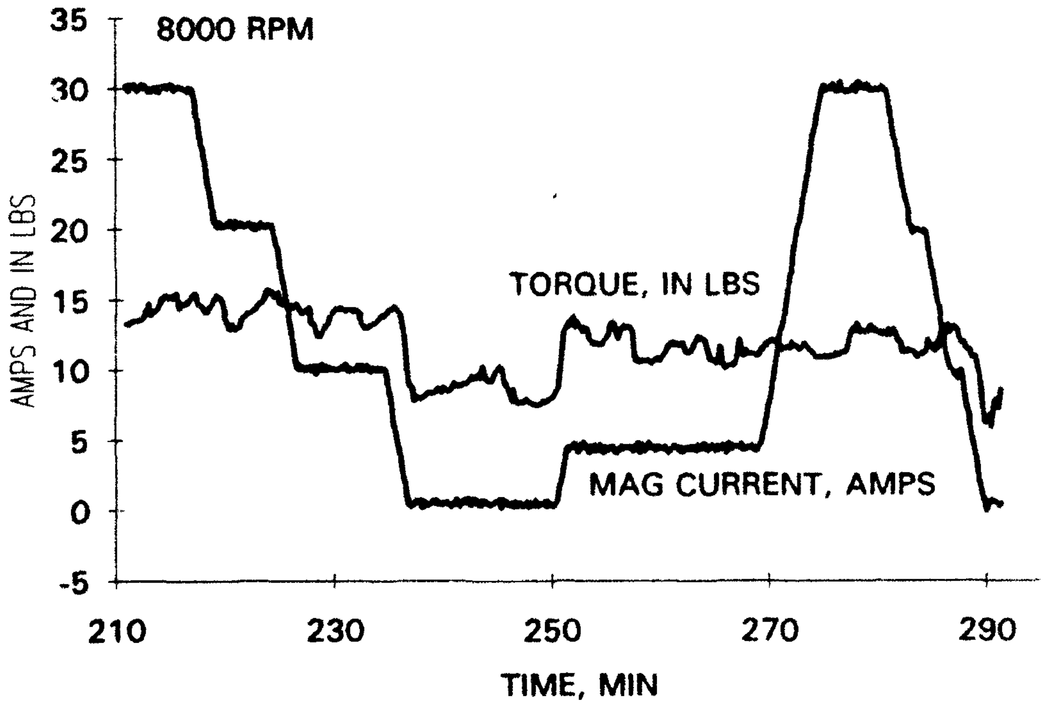

Fig. 6. Effect of magnetic field on bearing losses.

It can be seen that both the torque and the bearing temperature increase dramatically between 0 amps and 5 amps, but do not change much as the current is increased further. This is believed to be because even though the magnitude of the field increases, it's orientation also changes, so the radial component of the field in the bearing area, which generates the eddy currents, does not increase significantly. Furthermore, the torque increase, above no field values, compares well with predicted eddy current losses for ball bearings in magnetic fields.(Ref 5)

To eliminate as many unknown parameters as possible, and to prove that the losses were really in the bearings, the generator was run without liquid metal or braid from 2000 to 11,000 RPM and 0, 30, 60, and 90 amps magnet current. The losses measured were then the sum of the frictional losses (bearings, windage, and seals) and the bearing eddy current losses. These losses were subtracted from the runs with braid and liquid metal, and the difference was the liquid metal current collector losses.

COLLECTOR LOSSES

A comparison of the runs at 60 amps magnet current with and without collectors is shown in Fig. 7.

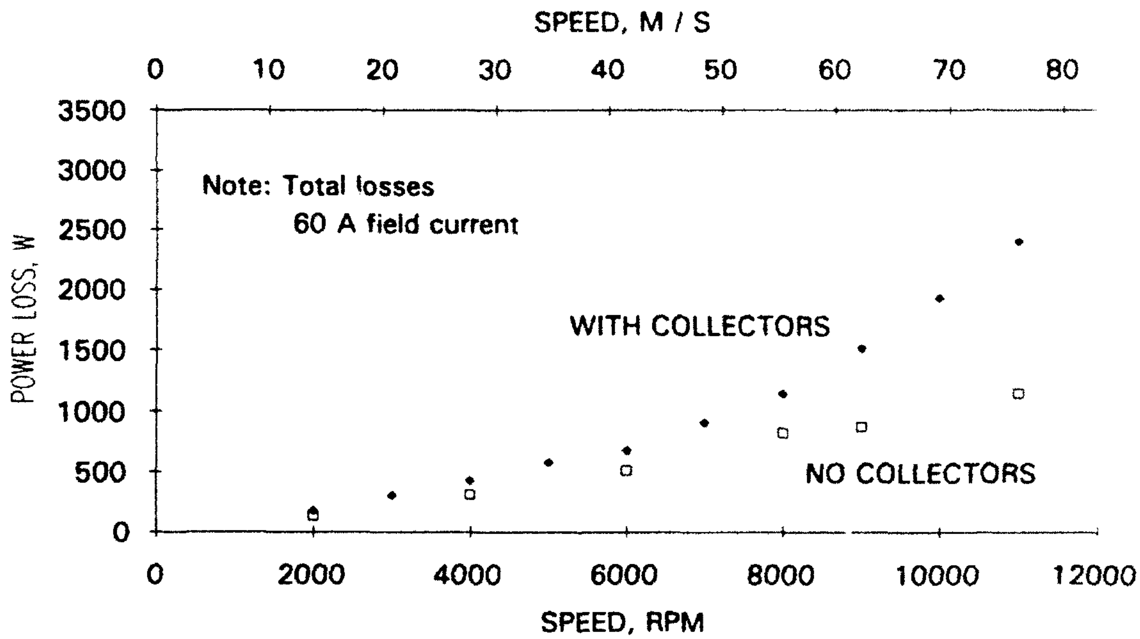

Fig 7. Comparison of losses with and without collectors.

The subtractions were performed for all the field levels, leaving the losses due to the collectors only, and the results are shown in Fig. 8.

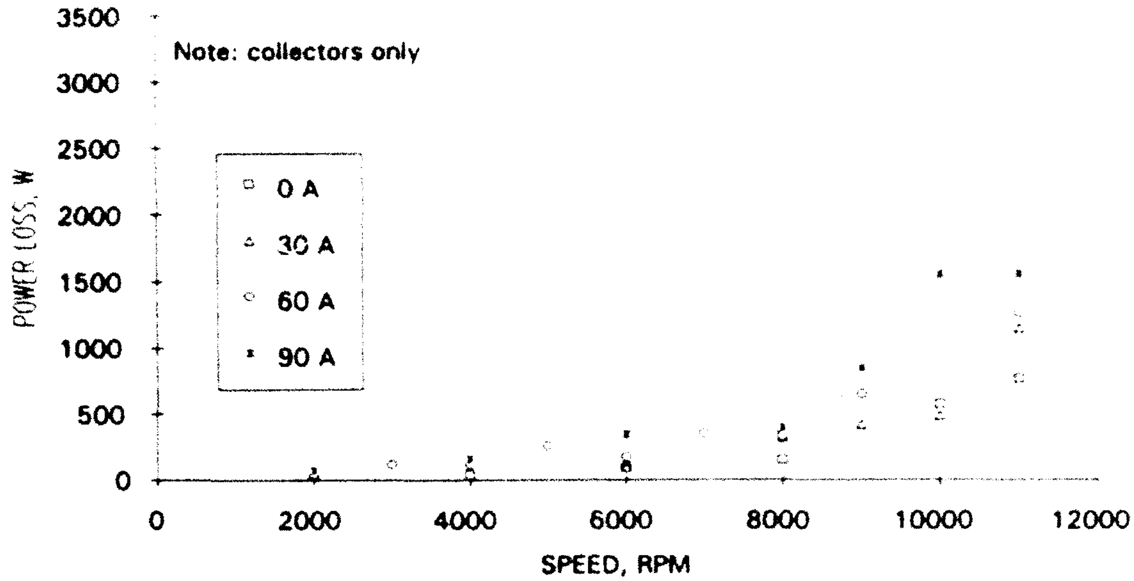

Fig. 8. Collector losses.

In contrast to the 1978 results, these data show a moderate dependence of the collector losses on field. The losses due to the magnetic field (in this case eddy current losses), are small compared to the ordinary fluid dynamic losses at the speeds tested.

INTERNAL RESISTANCE

The rotor resistance, measured separately while the machine was apart, was .96 micro ohms. The stators measured 2.1 micro ohms for the large stator, and 1.99 micro ohms for the small stator. The sum of the rotor and collectors together, when measured by running 200 amps through the generator at 2000 RPM and no magnetic field, was 5.7 micro ohms. So, when the rotor resistance is subtracted, the collector resistance is 4.74 micro ohms for both collectors at 2000 RPM. The total machine resistance is then 9.79 micro ohms at 2000 RPM.

COMPARISON WITH SIMPLE THEORY AND PREVIOUS DATA

Fig. 9 compares the experimental data to theoretical predictions using a simple one dimensional couette fluid loss model given below. (Ref. 4)

$$P = (\pi/4) f \rho v^3 r(w+k)$$

where:
- P = fluid dynamic power loss per collector, W
- f = Fanning friction factor = .007
- ρ = fluid mass density, kg/m^3
- v = collector rotor surface velocity, m/s
- w = collector width, m
- k = additional fluid contact width along radial sides of collector, m

Fig. 9 also compares present 1991 data to 1978 experimental data as corrected.

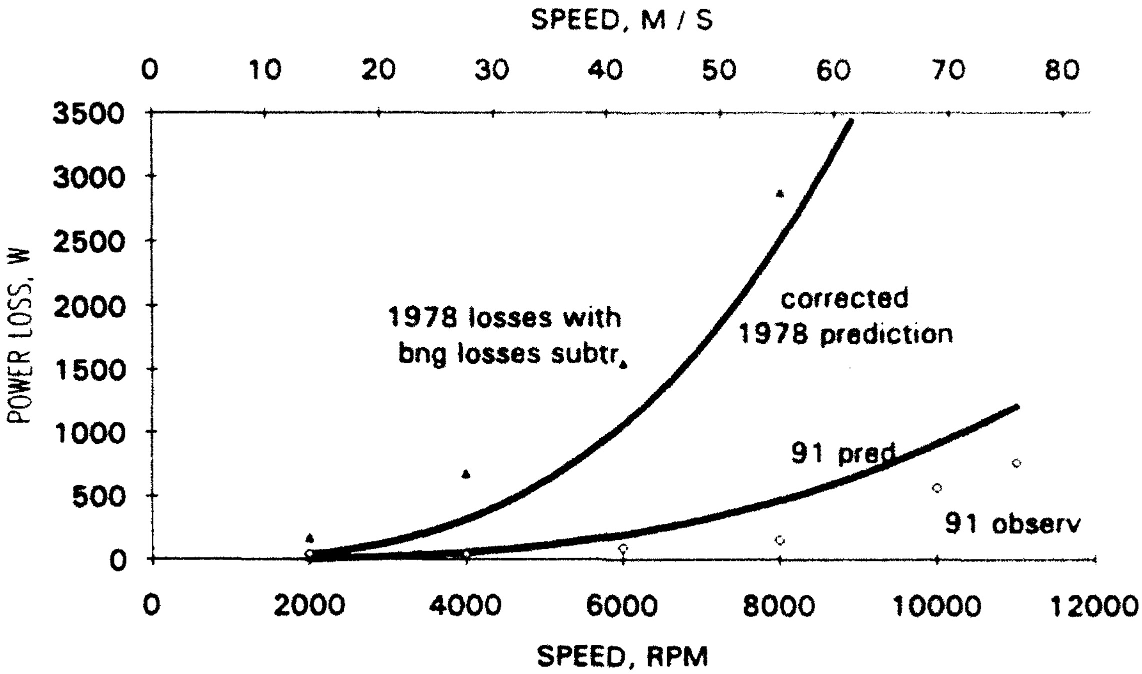

Fig. 9. Comparison of experimental data to theoretical prediction.

The 1978 experimental data was corrected by subtracting the bearing eddy current losses discussed above. Therefore, the plot of the experimental data from 1978 is lower than plotted originally in Fig. 3. The theoretical prediction for the 1978 data was also corrected. It had been assumed in 1978 that the height of the liquid metal on the sidewall (k/2) was zero. Recent calculations based on the fill levels of liquid metal indicate that the sidewall heights in 1978 were in the range of 20.3 mm (.799 in.) for the dewar end (small) collector and 16.9 mm (.664 in.) for the shaft end (large) collector. This drastically increases the predicted fluid losses for the 1978 data from Fig. 3. Consequently, after the reexamination of the 1978 data, there is approximately a 30% difference between measured and predicted data, rather than a factor of ten.

Furthermore, the simple couette flow model agrees with the 1991 experimental data within 30%. The fanning friction factor is not known precisely, and is estimated to be between .0055 and .007. Varying this number to .0055 would change the 1991 prediction to fit the 1991 data exactly but would result in poor correlation with the 1978 data.

Another factor that is not known exactly is the wetted area (w + k), since it is affected by the amount of liquid metal absorbed by the braid, which is uncertain.

The losses varied as much as 500 W due to fluctuation of the force of the cover gas seals on the rotor. The seals were designed to float on a layer of gas at high speed. Below 6000 RPM the cover gas seals (carbon face seals) rub directly on the rotor assembly material. Above 6000 RPM the gas film begin to be established, so the friction between the seals and the rotor decreases. For efficiency considerations, this fluctuation is of little consequence, but if the measured quantity of interest is in the 3 kW range, as current collector losses are, then these fluctuations are a significant portion of the experimental measurement.

The behavior of the cover gas seals was verified by monitoring the cover gas flow concurrently with the torque. A cover gas flow increase with a corresponding torque decrease would indicate that a lessening of the friction coefficient as the gas film is established is the reason for the torque decrease.

The torque does, in fact, vary as predicted with the cover gas flow as shown in Fig. 10. The correlation is not exact because the torque is influenced by other factors as well, such as vibration in the drive train at speeds over 8000 RPM.

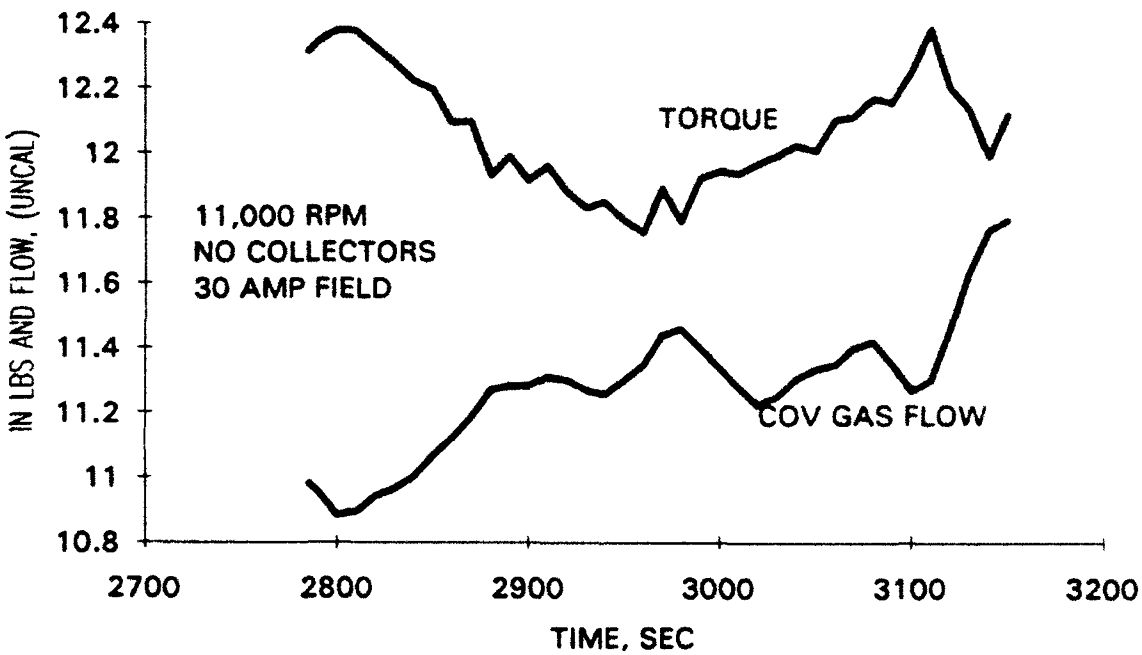

Fig. 10. Variation of torque with cover gas flow.

CONCLUSIONS AND FUTURE EXPERIMENTS

This work has resolved the question of why the losses in the 1978 generator current collector tests were so much greater than predicted. The answer is that they were not. The prediction simply did not take into account the eddy current losses in the bearings and the overfilling of the collectors with liquid metal, resulting in increased fluid losses. The actual collector losses are acceptably low and liquid metal current collectors remain an attractive option for high current homopolar machines. The fact that the cover gas seal losses fluctuate and change with speed was discovered.

Although the 300 kW generator is an excellent device for testing current collectors, improvements can be made to allow more accurate and reproducible measurements of the losses. First, the bearing eddy current losses could be eliminated with the use of ceramic bearings, allowing a more direct measurement of the current collector losses in future work. Second, the uncertainties caused by the cover gas seal force fluctuation could be eliminated by modifying the seal to commence floating at either lower or higher speeds so that the force would be constant in the range of the test. Running the generator as an unloaded motor would eliminate the vibrations caused by the drive motor and drive train resulting in cleaner data and allowing rotational speeds up to 20,000 RPM.

The theoretical model used in this work is a simple fluid loss model which predicted the experimental losses within 30%. It does not accurately predict magnetic field effects because the model (1) assumes infinite conductivity in the copper compared to the liquid metal and therefore, overestimates the eddy current losses in the collectors, and (2) does not include a secondary effect of the axial component of the field which reduces the eddy current losses. Analytical models are now being developed which include the finite conductivity of the braid and copper, as well as the axial field effects, in the eddy current calculation, preventing the gross overestimation of the eddy current losses given by the 1 D turbulent couette model. Furthermore, theoretical models are being developed which incorporate more sophisticated turbulent models, transient, and temperature effects. The data presented herein will serve as a guide in this development.

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